

Dark Matter “Collider” from Inelastic Boosted Dark Matter

Doojin Kim,^{1,2} Jong-Chul Park,³ and Seodong Shin^{4,5}

¹Theory Division, CERN, CH-1211 Geneva 23, Switzerland

²Department of Physics, University of Florida, Gainesville, FL 32611, USA

³Department of Physics, Chungnam National University, Daejeon 305-764, Korea

⁴Physics Department, Indiana University, Bloomington, IN 47405, USA

⁵Department of Physics & IPAP, Yonsei University, Seoul 03722, Korea

(Dated: December 22, 2016)

We propose a *novel* dark matter (DM) detection strategy for the models with non-minimal dark sector. The main ingredients in the underlying DM scenario are a boosted DM particle and a heavier dark sector state. The relativistic DM impinged on target material scatters off *inelastically* to the heavier state which subsequently decays into DM along with lighter states including visible (Standard Model) particles. The expected signal event, therefore, accompanies a visible signature by the secondary cascade process associated with a recoiling of the target particle, differing from the typical neutrino signal *not* involving the secondary signature. We then discuss various kinematic features followed by DM detection prospects at large volume neutrino detectors with a model framework where a dark gauge boson is the mediator between the Standard Model particles and DM.

PACS numbers:

Introduction. A tremendous amount of effort has been made to detect non-gravitational signals of dark matter (DM) in direct detection, indirect detection, and collider experiments. Most of them, however, have provided strong constraints on DM models rather than unambiguous discovery signatures. This fact has recently motivated research programs to study non-conventional DM scenarios such as secluded DM [1–8] and non-minimal dark sector models including assisted freeze-out [9], boosted DM (BDM) [10–13], dark cascade scenarios [14, 15], and multi-component DM [16–23].

Promising strategies to examine those possibilities include the observation of relativistic DM scattering with targets in terrestrial experiments to overcome its small interaction with Standard Model (SM) particles and the search for boosted dark sector objects. Large volume neutrino detectors [10] and fixed target experiments with high intensity [24, 25] can probe relevant signals. We remark that the search scheme in both cases is based on simple number counting over the expected number of background events. Indeed, this scheme has intrinsic limitation: in particular for neutrino detectors, it is hard to discern a relativistic scattering signal of DM from a neutrino scattering event, the main *irreducible* background.

In this letter, we propose a *novel* channel which takes a key role in search for the relativistic DM scattering signals arising in various models comprising an additional (unstable) dark sector particle. This is schematically depicted in Fig. 1 where the scattered dark sector particle (denoted by χ_2) differs from the incoming DM (denoted by χ_1), i.e., an inelastic scattering occurs in the recoil of the target. Furthermore, χ_2 is heavier than χ_1 so that the former subsequently decays into lighter states including the latter and visible SM particles, which is reminiscent of typical cascade decay signatures in collider experiments. The expected signal, therefore, involves a recoiling of target material and (visible) decay products from the sec-

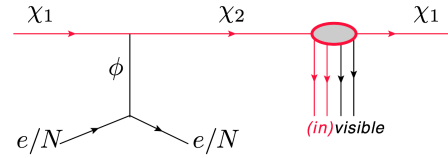


FIG. 1: Inelastic boosted DM direct detection scenarios under consideration.

ondary process of χ_2 , which is clearly distinctive from high energetic neutrino signatures.

Model framework. To validate the DM scenario explained above, we first delineate a DM model framework which contains the cascade process depicted in Fig. 1. Employing a Dirac fermionic DM χ_1 for simplicity, we assume that it interacts with target SM particles (e.g., electron or nucleus) via a *t*-channel exchange of the mediator ϕ . As stated earlier, we further assume that the outgoing dark sector particle is *not* χ_1 but a heavier unstable particle χ_2 (i.e., $m_{\chi_2} > m_{\chi_1}$). In principle, the mediator ϕ can be either a SM or a new physics particle but we take a “dark” gauge boson X_μ for simplicity from the following toy model Lagrangian with a dark U(1)_X gauge symmetry:

$$\mathcal{L}_X \supset -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{12} \bar{\chi}_2 \gamma^\mu \chi_1 X_\mu + h.c., \quad (1)$$

where the first term describes the kinetic mixing between U(1)_X and U(1)_{EM} [1, 5, 26–29] parameterized by ϵ . The off-diagonal gauge interaction of χ_1 and χ_2 with X_μ appears in the second term with coupling g_{12} . We expect that such a vertex may arise, for example, from the mixing in the dark sector after imposing different U(1)_X charges to χ_1 and χ_2 (see also Ref. [30] for the mixing in the SM quark sector with a visible U(1)[′] symmetry). More concrete model building including other possible

scenarios (e.g., Higgs portal) will be available in our future work [31].

The heavier nature of χ_2 renders its decay eventually into χ_1 plus SM or other (invisible) dark sector particles. Such a decay, in general, proceeds via a sequential cascade process as symbolized by a red-circled blob in Fig. 1. Hence, the expected signal event is featured by a recoil of the target SM particle, accompanying secondary signatures from the cascade decay process. As a minimal choice, we take a single-step cascade decay of χ_2 throughout this letter, i.e., χ_2 decays back into χ_1 and ϕ by the interactions in Eq. (1).

We first calculate the matrix element squared for the scattering process $\chi_1 T \rightarrow \chi_2 T$ with T denoting the associated target:

$$\begin{aligned} |\overline{\mathcal{M}}|^2 = & \frac{8(\epsilon e g_{12})^2 m_T}{\{2m_T(E_{\chi_2} - E_{\chi_1}) - m_\phi^2\}^2} \\ & \times \left[\mathcal{M}_0(F_1 + \kappa F_2)^2 + \mathcal{M}_1 \left\{ -(F_1 + \kappa F_2)\kappa F_2 \right. \right. \\ & \left. \left. + \frac{(\kappa F_2)^2}{4m_T}(E_{\chi_1} - E_{\chi_2} + 2m_T) \right\} \right]. \quad (2) \end{aligned}$$

Here \mathcal{M}_0 and \mathcal{M}_1 are defined as follows:

$$\begin{aligned} \mathcal{M}_0 = & \left[m_T(E_{\chi_1}^2 + E_{\chi_2}^2) - \frac{(\delta m_\chi)^2}{2}(E_{\chi_2} - E_{\chi_1} + m_T) \right. \\ & \left. + m_T^2(E_{\chi_2} - E_{\chi_1}) + m_{\chi_1}^2 E_{\chi_2} - m_{\chi_2}^2 E_{\chi_1} \right], \quad (3) \end{aligned}$$

$$\begin{aligned} \mathcal{M}_1 = & m_T \left[\left\{ (E_{\chi_1} + E_{\chi_2}) - \frac{m_{\chi_2}^2 - m_{\chi_1}^2}{2m_T} \right\}^2 \right. \\ & \left. + (E_{\chi_1} - E_{\chi_2} + 2m_T) \left\{ (E_{\chi_2} - E_{\chi_1}) - \frac{(\delta m)^2}{2m_T} \right\} \right], \quad (4) \end{aligned}$$

where $\delta m_\chi \equiv m_{\chi_2} - m_{\chi_1}$ and $E_{\chi_{1(2)}}$ is the $\chi_{1(2)}$ energy measured in the laboratory frame. [44] For the two form factors F_1 and F_2 , we set them to be 1 and 0 for the electron target (or e -scattering), whereas we employ nontrivial values as per Ref. [32] for the proton target (or p -scattering) together with the proton anomalous magnetic moment $\kappa = 1.79$.

Kinematic features. We now discuss interesting kinematic features arising in the model framework discussed earlier. Like ordinary colliders, the maximum mass reach of χ_2 is $\sqrt{s} - m_T$ with \sqrt{s} being the overall center-of-mass energy (i.e., $s = m_T^2 + 2E_{\chi_1}m_T + m_{\chi_1}^2$):

$$m_{\chi_2} \leq \sqrt{m_T^2 + 2E_{\chi_1}m_T + m_{\chi_1}^2} - m_T. \quad (5)$$

If χ_1 is much heavier than the target (i.e., $m_{\chi_1} \gg m_T$) along with a decent boost γ_{χ_1} , the above relation is approximated to

$$m_{\chi_2} \lesssim m_{\chi_1} + (\gamma_{\chi_1} - 1)m_T, \quad (6)$$

to which our e -scattering corresponds. On the other hand, the opposite limit, $m_{\chi_1} \ll m_T$, results in

$$m_{\chi_2} \lesssim \gamma_{\chi_1} m_{\chi_1}, \quad (7)$$

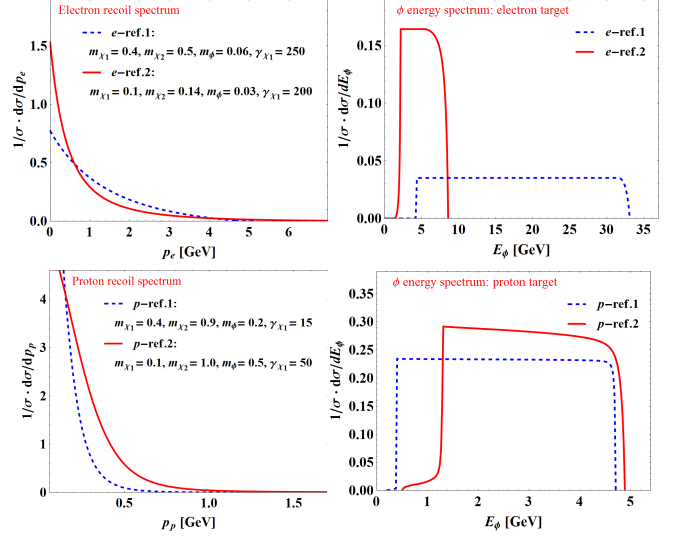


FIG. 2: Expected unit-normalized energy spectra of the recoiling target particles from the primary vertex (left panels) and outgoing mediators from the secondary vertex (right panels) for e -scattering (top panels) and p -scattering (bottom panels). The reference masses are in unit of GeV.

allowing us to probe much heavier dark sector states than the incoming DM, which is possible for p -scattering.

We next discuss the expected energy spectra of the recoiling target and the visible particles from the secondary vertex. In the laboratory frame, the differential cross section is

$$\frac{d\sigma}{dE_T} = \frac{m_T}{8\pi\lambda(s, m_T^2, m_{\chi_1}^2)} |\overline{\mathcal{M}}|^2, \quad (8)$$

where E_T is the energy of the recoiling target and $\lambda(x, y, z) = (x - y - z)^2 - 4yz$. Here $|\overline{\mathcal{M}}|^2$ is expressed in terms of $E_T = E_{\chi_1} + m_T - E_{\chi_2}$. Note that the recoil energy in usual direct detection experiments corresponds to the magnitude of the spatial momentum (equivalently, the kinetic energy) of the recoiling target, i.e., $p_T = \sqrt{E_T^2 - m_T^2}$. We find that kinematically allowed maximum (minimum) recoil energy E_T^+ (E_T^-) is given by

$$E_T^\pm = \frac{s + m_T^2 - m_{\chi_2}^2}{2\sqrt{s}} \frac{E_{\chi_1} + m_T}{\sqrt{s}} \pm \frac{\lambda^{1/2}(s, m_T^2, m_{\chi_2}^2)}{2\sqrt{s}} \frac{p_{\chi_1}}{\sqrt{s}}, \quad (9)$$

where $p_{\chi_1} = \sqrt{E_{\chi_1}^2 - m_{\chi_1}^2}$. The upper-left panel (e -scattering) and the lower-left panel (p -scattering) in Fig. 2 demonstrate expected unit-normalized recoil energy spectra for our four reference points (e -ref.1, e -ref.2, p -ref.1, and p -ref.2) as detailed in the plots. Note that the differential cross section is greater for the smaller momentum transfer as expected in Eq. (2).

The spectral behavior in the distribution of ϕ energy E_ϕ , in principle, depends on the relevant vertex structure. In our toy model, due to the vector-like nature

Exp.	Volume [Mt]	E_e^{th} [GeV]	E_p^{th} [GeV]	θ_e^{res} [°]	θ_p^{res} [°]
SK	0.0224	0.1	1.07	3	3
HK	0.56	0.1	1.07	3	3
DUNE	0.04	0.03	0.05	1	5

TABLE I: Summary of the volume, threshold energy, and angular resolution of considered experiments from Refs. [41], [42], and [43] for SK, HK, and DUNE, respectively. E_e^{th} at SK/HK could be lowered below 0.1 GeV with worse angular resolution. On the other hand, angular resolution gets better with higher p_T .

of the mediator coupling, χ_2 is produced in an unpolarized way, so that it can be treated *effectively* as a scalar. For a simple two-body decay, the energy spectra of decay products have been extensively examined in the context of collider phenomenology [33–39] and cosmic ray phenomenology [14, 15, 22, 23, 40]. For generality, we consider the case that m_ϕ is not negligible, finding the following expression based on the formulation in Ref. [38]:

$$\frac{d\sigma}{dE_\phi} = \int d\gamma_{\chi_2} \frac{d\sigma}{d\gamma_{\chi_2}} \frac{1}{2E_\phi^* \sqrt{\gamma_{\chi_2}^2 - 1}}, \quad (10)$$

where E_ϕ^* is the ϕ energy measured in the χ_2 rest frame. The detailed expressions for the integral range are not illustrative, so we instead refer to Refs. [31, 38]. Here the boost distribution of χ_2 , $d\sigma/d\gamma_{\chi_2}$, can be easily obtained from the χ_2 energy spectrum, which is, in turn, derived from Eq. (8) with E_T replaced by $E_{\chi_1} + m_T - E_{\chi_2}$.

The expected (unit-normalized) energy spectra of ϕ produced in the cascade process for our reference points are exhibited in the upper-right panel (e -scattering) and the lower-right panel (p -scattering) in Fig. 2, respectively. For the chosen reference points, we find that E_{χ_2} values are highly localized towards the kinematic endpoint, and therefore, the resulting ϕ energy spectrum appears almost box-like.

In practice, the energy of ϕ can be measured from its visible decay products. Throughout this letter, we assume that the mediator ϕ predominantly decays into e^+e^- and $\chi_2 \rightarrow \chi_1\phi \rightarrow \chi_1e^+e^-$ proceeds promptly. [45] Again, a signal event is characterized by a recoiling target (e or p) and a e^+e^- pair, so the angular separations among them would be critical to identify the signal events, which will be discussed in the next section.

Detection prospects. Based on the signal features discussed so far, we are now in the position to assess the detection prospects of our signal. In order for our signal to be sensitive even with small flux, we choose large volume neutrino detectors: Super-Kamiokande (SK), Hyper-Kamiokande (HK), and Deep Underground Neutrino Experiment (DUNE) where the latter two are future proposals. We summarize their key attributes in Table I. Note that future fixed target experiments with high intensity can be also used to observe our signal, which will be examined in the future work [31].

The energy and angular resolutions for e -scattering

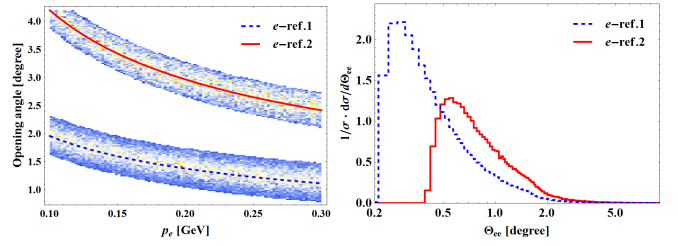


FIG. 3: Left panel: angular separation between the recoiling target and χ_2 (red solid and blue dashed lines) or the mediator ϕ (temperature-scaled regions). Right panel: angular separation between the e^+e^- pair from the ϕ decay.

are usually better than those for p -scattering, especially in SK/HK. This is because large momentum transfer above $m_p = 0.938$ GeV is required for the recoiling proton to produce Cherenkov radiation ($p_p \gtrsim 1.07$ GeV for SK/HK [41]). Note that this requirement is rather relaxed in liquid Ar detectors like DUNE. Reminding the trend that the differential cross section is larger for smaller momentum transfer, one can expect that e -scattering is preferred over p -scattering in SK/HK if focusing only on the recoil signal. For p -scattering, we further restrict ourselves to $p_p \lesssim 1.8$ GeV to avoid the possibility of deep inelastic scattering.

As stated before, observation of the secondary cascade signal plays the key role in discovery of our DM signal. We point out that the visible particles are often collimated due to the large boost of the incident DM. Therefore, unambiguous signal identification depends on what extent we can separate those (highly) collimated signals beyond the angular resolutions of the detectors. Defining θ_{χ_2} as the angle between the recoiling target and χ_2 in the laboratory frame, we obtain

$$\cos \theta_{\chi_2} = \frac{E_T E_{\chi_2} + (m_T^2 + m_{\chi_2}^2 - s)/2}{\sqrt{(E_{\chi_2}^2 - m_{\chi_2}^2)(E_T^2 - m_T^2)}}. \quad (11)$$

The value θ_{χ_2} roughly determines the angular separation between the primary and secondary signals when χ_2 , ϕ , and the decay products (e^+e^-) are highly collimated. This is true for e -scattering as shown in the left panel of Fig. 3. The red solid and blue dashed lines (temperature-scaled bands) show the angle between the recoiling target and χ_2 (ϕ), from which we clearly see that χ_2 and ϕ are collimated. We further check that the angular separation between e^+ and e^- from the ϕ decay are mostly within 1.5° as shown in the right panel of Fig. 3. Adopting the angular resolution 3° for SK/HK, we find that our reference point e -ref.2 manifests two separable signatures for most momentum values of the recoiling electron $p_e \in [0.1, 0.3]$ GeV (see also Table I). [46]

On the other hand, larger angular separation is possible for our p -scattering reference points because E_{χ_1} , m_p , and m_{χ_2} are roughly of the same order so that typical χ_2 's are neither too boosted nor too aligned along the

Exp.	Run time	e -ref.1	e -ref.2	p -ref.1	p -ref.2
SK	13.6 yr	170	7.1	3500	5200
HK	1 yr	88	3.7	1900	2800
HK	13.6 yr	6.7	0.28	140	210
DUNE	1 yr	190	9.0	150	1600
DUNE	13.6 yr	14	0.69	11	120

TABLE II: Required fluxes in unit of $10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ with which our reference points become sensitive in various experiments.

recoiling proton direction. In addition, we observe that the opening angle of ϕ decay products (defined as Θ_{ee}) gets larger. Given a mediator boost factor γ_ϕ , we find

$$\Theta_{ee} \simeq \arccos \left[1 - \frac{2}{\gamma_\phi^2 \sin^2 \theta + \cos^2 \theta} \right], \quad (12)$$

where θ is the emission angle of one of the decay products with respect to the ϕ boost direction in the ϕ rest frame. Here we took the fact that $m_\phi \gg m_e$ for all our reference points. It is easy to see that the opening angle is greater than 6° for all possible θ as far as $\gamma_\phi \lesssim 20$. We then find that our reference points selected for p -scattering are anticipated to have three resolvable signatures in most of the allowed phase space, whereas those for e -scattering would involve two signatures. This is an unarguable advantage of p -scattering although the cross section is smaller than that for e -scattering.

In both e -scattering and p -scattering cases, we expect to observe two or three separate signatures, which are not expected in usual neutrino scattering. So it is fair to obtain the experimental sensitivity by requiring three signal events under a zero-background assumption, while we leave more systematic background analysis to the future work. We list the minimum required fluxes of χ_1 making our reference points sensitive in SK, HK, and DUNE in Table II. Considering the fact that the typical flux of χ_1 demanded in the minimal BDM setup is $\mathcal{O}(10^{-7}) \text{ cm}^{-2} \text{ s}^{-1}$ [10], we see that e -ref. 2 is rather *promising*. The other reference points can be also probed once we consider a modified BDM setup to increase the flux up to $\mathcal{O}(10^{-4}) \text{ cm}^{-2} \text{ s}^{-1}$ [12, 13] or fixed target experiments with much higher intensity. Note that the sensitivities in HK 1-year is much better, compared to SK 13.6-year, mainly due to the bigger volume. For p -scattering we observe that the sensitivities increase in DUNE due to its remarkably lower E_p^{th} .

We finally conduct a parameter scan to check the viability of our signal processes in a wider range of space. Fixing $m_\phi = 0.03$ (0.2) GeV, $\epsilon = 3 \times 10^{-4}$, and $g_{12} = 0.5$, we obtain the allowed parameter region of $e(p)$ -scattering in m_{χ_1} vs. γ_{χ_1} plane for $\delta m_\chi = 0.1, 0.2$ GeV (0.5, 1, 1.5, 2 GeV) and show them in the upper (lower) panels of Fig. 4. The left (right) panels are for SK/HK (DUNE). The black contours represent the maximally possible m_{χ_2} for a given set of m_{χ_1} and γ_{χ_2} (see Eq. (5) as well). Minimally required χ_1 fluxes for our signal to be sensitive

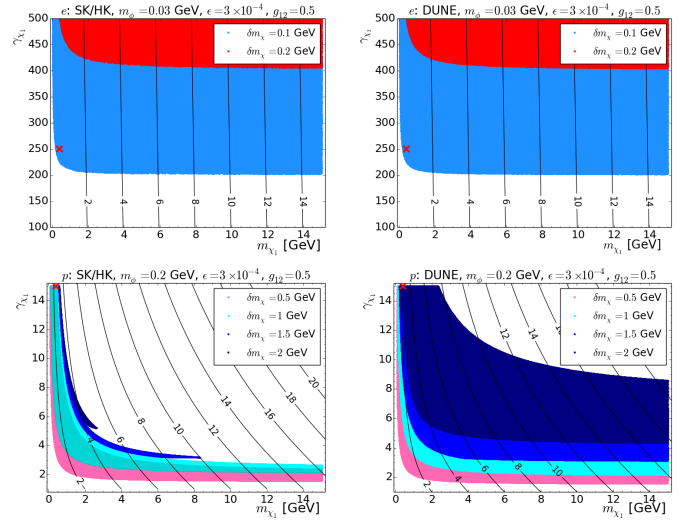


FIG. 4: e -scattering (upper panels) and p -scattering (lower panels) parameters in SK and HK (left panels) and DUNE (right panels) for $m_\phi = 0.2$ GeV. For e -scattering we scan for $\delta m_\chi = 0.1, 0.2$ GeV while $\delta m_\chi = 0.5, 1, 1.5, 2$ GeV for p -scattering.

in each experiment are an order of magnitude smaller than (of the same order as) those for e -scattering (p -scattering) in Table II. The red “X” points denote the reference points: e -ref.1 and p -ref.1.

Conclusions and outlook. In this letter, we proposed a novel DM detection strategy for the models with non-minimal dark sector involving a heavier unstable particle. Once boosted DM inelastically scatters off target material and produces a heavier dark sector particle, secondary signatures may arise in associated with the target recoil, as shown in Fig. 1. This signal feature clearly differs from relativistic neutrino scattering events, which offers a *new paradigm* in probing non-minimality of the dark sector. We also investigated the detection prospects of relevant DM signals at large volume neutrino detectors, and found promising. Similar analyses will be straightforwardly applicable to future fixed target experiments.

It is possible to study more complicated signatures such as multi-step cascade decays although we employed the simplest secondary process in this letter. Furthermore, we expect proactive utilization of the knowledge from collider phenomenology due to the similarity of the proposed DM scenario with typical collider signatures, when detectors are designed and implemented accordingly in the future. As a concluding remark, we strongly encourage DM-related intensity-frontier collaborations (e.g., beam-dump experiments) to pay their attention to the DM detection strategy proposed in this letter and conduct relevant DM searches.

Acknowledgments

We thank K. Agashe, M. Aoki, J.-H. Huh, D. Kim, K. Kong, K. Matchev, T. Saab, C. S. Shin, M. Son, and J. Yoo for insightful/useful discussions. We appreciate Brookhaven Forum 2015 for its encouraging environment enabling us to initiate this project, and CETUP* (Center for Theoretical Underground Physics and Related Ar-

eas), Santa Fe LHC summer workshop 2016, and Focus Workshop on Particle Physics and Cosmology by IBS-CTPU for their hospitality during the completion of this work. DK was supported in part by DOE Grant DE-SC0010296, and is presently supported by the Korean Research Foundation (KRF) through the CERN-Korea Fellowship program. JCP is supported by the National Research Foundation of Korea (NRF-2016R1C1B2015225).

-
- [1] J. H. Huh, J. E. Kim, J. C. Park and S. C. Park, Phys. Rev. D **77**, 123503 (2008) [arXiv:0711.3528 [astro-ph]].
 - [2] M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B **662**, 53 (2008) [arXiv:0711.4866 [hep-ph]].
 - [3] Y. G. Kim, K. Y. Lee and S. Shin, JHEP **0805**, 100 (2008) [arXiv:0803.2932 [hep-ph]].
 - [4] Y. G. Kim and S. Shin, JHEP **0905**, 036 (2009) [arXiv:0901.2609 [hep-ph]].
 - [5] E. J. Chun, J. C. Park and S. Scopel, JHEP **1102**, 100 (2011) doi:10.1007/JHEP02(2011)100 [arXiv:1011.3300 [hep-ph]].
 - [6] J. C. Park and S. C. Park, Phys. Lett. B **728**, 41 (2014) doi:10.1016/j.physletb.2013.11.027 [arXiv:1305.5013 [hep-ph]].
 - [7] G. Belanger, A. Goudelis, J. C. Park and A. Pukhov, JCAP **1402**, 020 (2014) doi:10.1088/1475-7516/2014/02/020 [arXiv:1311.0022 [hep-ph]].
 - [8] Y. G. Kim, K. Y. Lee, C. B. Park and S. Shin, Phys. Rev. D **93**, no. 7, 075023 (2016) [arXiv:1601.05089 [hep-ph]].
 - [9] G. Belanger and J. C. Park, JCAP **1203**, 038 (2012) [arXiv:1112.4491 [hep-ph]].
 - [10] K. Agashe, Y. Cui, L. Necib and J. Thaler, JCAP **1410**, no. 10, 062 (2014) [arXiv:1405.7370 [hep-ph]].
 - [11] J. Berger, Y. Cui and Y. Zhao, JCAP **1502**, no. 02, 005 (2015) [arXiv:1410.2246 [hep-ph]].
 - [12] K. Kong, G. Mohlabeng and J. C. Park, Phys. Lett. B **743**, 256 (2015) doi:10.1016/j.physletb.2015.02.057 [arXiv:1411.6632 [hep-ph]].
 - [13] H. Alhazmi, K. Kong, G. Mohlabeng and J. C. Park, arXiv:1611.09866 [hep-ph].
 - [14] D. Kim and J. C. Park, Phys. Dark Univ. **11**, 74 (2016) [arXiv:1507.07922 [hep-ph]].
 - [15] D. Kim and J. C. Park, Phys. Lett. B **750**, 552 (2015) [arXiv:1508.06640 [hep-ph]].
 - [16] K. R. Dienes and B. Thomas, Phys. Rev. D **85**, 083523 (2012) [arXiv:1106.4546 [hep-ph]].
 - [17] K. R. Dienes and B. Thomas, Phys. Rev. D **85**, 083524 (2012) [arXiv:1107.0721 [hep-ph]].
 - [18] K. R. Dienes, J. Kumar and B. Thomas, Phys. Rev. D **86**, 055016 (2012) [arXiv:1208.0336 [hep-ph]].
 - [19] K. R. Dienes, J. Kumar and B. Thomas, Phys. Rev. D **88**, no. 10, 103509 (2013) [arXiv:1306.2959 [hep-ph]].
 - [20] K. R. Dienes, S. Su and B. Thomas, Phys. Rev. D **86**, 054008 (2012) [arXiv:1204.4183 [hep-ph]].
 - [21] K. R. Dienes, S. Su and B. Thomas, Phys. Rev. D **91**, no. 5, 054002 (2015) [arXiv:1407.2606 [hep-ph]].
 - [22] K. K. Boddy, K. R. Dienes, D. Kim, J. Kumar, J. C. Park and B. Thomas, Phys. Rev. D **94**, no. 9, 095027 (2016) doi:10.1103/PhysRevD.94.095027 [arXiv:1606.07440 [hep-ph]].
 - [23] K. K. Boddy, K. R. Dienes, D. Kim, J. Kumar, J. C. Park and B. Thomas, arXiv:1609.09104 [hep-ph].
 - [24] B. Batell, M. Pospelov and A. Ritz, Phys. Rev. D **80**, 095024 (2009) doi:10.1103/PhysRevD.80.095024 [arXiv:0906.5614 [hep-ph]].
 - [25] P. deNiverville, M. Pospelov and A. Ritz, Phys. Rev. D **84**, 075020 (2011) doi:10.1103/PhysRevD.84.075020 [arXiv:1107.4580 [hep-ph]].
 - [26] L. B. Okun, Sov. Phys. JETP **56**, 502 (1982) [Zh. Eksp. Teor. Fiz. **83**, 892 (1982)].
 - [27] P. Galison and A. Manohar, Phys. Lett. B **136**, 279 (1984). doi:10.1016/0370-2693(84)91161-4
 - [28] B. Holdom, Phys. Lett. B **166**, 196 (1986). doi:10.1016/0370-2693(86)91377-8
 - [29] J. C. Park and S. C. Park, Phys. Lett. B **718**, 1401 (2013) doi:10.1016/j.physletb.2012.12.035 [arXiv:1207.4981 [hep-ph]].
 - [30] J. E. Kim, M. S. Seo and S. Shin, Phys. Rev. D **83**, 036003 (2011) [arXiv:1010.5123 [hep-ph]].
 - [31] D. Kim, J. C. Park and S. Shin, work in progress.
 - [32] I. A. Qattan *et al.*, Phys. Rev. Lett. **94**, 142301 (2005) doi:10.1103/PhysRevLett.94.142301 [nucl-ex/0410010].
 - [33] K. Agashe, R. Franceschini and D. Kim, Phys. Rev. D **88**, no. 5, 057701 (2013) doi:10.1103/PhysRevD.88.057701 [arXiv:1209.0772 [hep-ph]].
 - [34] K. Agashe, R. Franceschini, D. Kim and K. Wardlow, Phys. Dark Univ. **2**, 72 (2013) doi:10.1016/j.dark.2013.03.003 [arXiv:1212.5230 [hep-ph]].
 - [35] K. Agashe, R. Franceschini and D. Kim, JHEP **1411**, 059 (2014) doi:10.1007/JHEP11(2014)059 [arXiv:1309.4776 [hep-ph]].
 - [36] C. Y. Chen, H. Davoudiasl and D. Kim, Phys. Rev. D **89**, no. 9, 096007 (2014) doi:10.1103/PhysRevD.89.096007 [arXiv:1403.3399 [hep-ph]].
 - [37] K. Agashe, R. Franceschini, D. Kim and K. Wardlow, JHEP **1605**, 138 (2016) doi:10.1007/JHEP05(2016)138 [arXiv:1503.03836 [hep-ph]].
 - [38] K. Agashe, R. Franceschini, S. Hong and D. Kim, JHEP **1604**, 151 (2016) doi:10.1007/JHEP04(2016)151 [arXiv:1512.02265 [hep-ph]].
 - [39] K. Agashe, R. Franceschini, D. Kim and M. Schulze, arXiv:1603.03445 [hep-ph].
 - [40] F. W. Stecker, "Cosmic gamma rays," NASA Special Publication **249** (1971).
 - [41] M. Fechner *et al.* [Super-Kamiokande Collaboration], Phys. Rev. D **79**, 112010 (2009) doi:10.1103/PhysRevD.79.112010 [arXiv:0901.1645 [hep-ex]].
 - [42] E. Kearns *et al.* [Hyper-Kamiokande Working Group Collaboration], arXiv:1309.0184 [hep-ex].
 - [43] R. Acciarri *et al.* [DUNE Collaboration],

- arXiv:1512.06148 [physics.ins-det].
- [44] Obviously, for the fixed target experiments, the target frame is the same as the laboratory frame.
 - [45] Depending on m_ϕ and ϵ , one may also consider an appreciable displaced vertex in the decay $\chi_2 \rightarrow \chi_1 e^+ e^-$. We defer the study in this direction to the future work [31].
 - [46] For e -ref.1, detecting events with separable signatures is very challenging according to the left panel of Fig. 3, which enforces us to perform a more careful analysis in regard to angular separation by considering both the recoil electron and the $e^+ e^-$ pair from the ϕ decay.